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THE FLOW RESISTANCE OF HEPA FILTERS IN SUPERSATURATED AIRSTREAMS*

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Abstract

A loss of coolant accident or fire suppression with water sprays would release free moisture into the air within the containment building of a nuclear reactor. The resulting high air humidity could be expected to unfavorably affect the behavior of the HEPA filters in the facility air cleaning systems. Still to be found in the literature are instances of moisture related deterioration in filter performance during less serious incidents, and even during normal operations. One phenomenon which contributes to filter failure, and which also causes air-cleaning system malfunction characterized by drastically reduced flow rates, is the increase in filter differential pressure resulting from supersaturated airflow.

In order to better evaluate the performance and the reliability of filters exposed to fog, a study of the factors which influence filter pressure drop was carried out in tests of clean and dust loaded full scale HEPA-filter units. Investigated were the effects of several airstream parameters and such filter characteristics as manufacturer, design, pack geometry, extent and type of dust loading, as well as pleat orientation to the airflow. A discontinuous gravimetric method employing full-size filter units as sampling filters was successfully implemented to determine the average liquid moisture content of the airstream with an uncertainty of $\leq 10\,\%$.

The dust loading in filters removed from service and the liquid moisture content of the air proved to most adversely affect the rate and extent of the pressure drop increase. Reductions in the susceptibility of clean filters to pressure drop increases can be obtained by changes in filter geometry, design or orientation to the airflow that enhance the drainage of water from the filter medium. However, the predominance of the adverse influence of dust loading appears to be able to counteract the effectiveness of the improvements studied.

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I. Introduction

Maintaining effective particulate filtration in airstreams under abnormal conditions involving high humidity is one important challenge posed in providing for the reliability of air cleaning processes within nuclear facilities during accident situations. The relatively fragile High Efficiency Particulate Air (HEPA) filter units in air cleaning systems play a crucial role in preventing the release of airborne radioactivity from contaminated zones. Filter behavior under adverse operating conditions which might be expected to follow an accident continues to be investigated: particularly with regard to improving and qualifying filter performance, as reported here. The empirical data needed to model the flow dynamics within air cleaning systems under accident conditions are also being pursued.

Supersaturated Airstreams in Air Cleaning Systems

Some thirty years of development have resulted in filter units characterized by advanced levels of performance and reasonable costs /1–4/. However, as evident by persistent reports in the literature /5, literature survey in 6/, one remaining weak point in filter design is a suceptibility to deterioration or failure in humid airflows. This is a serious drawback with respect to the possible introduction of significant amounts of sensible moisture into the air within containment areas resulting from fire extinguishing measures or a loss–of–coolant accident (LOCA).

Even in operations considered to be otherwise normal, air may enter an air cleaning system with an inocuous relative humidity and yet arrive at the filter units with a potentially harmful, higher relative humidity or in a more threatening, saturated state. The diversion of airstreams to parallel or to standby systems which initially have a temperature less than the air dew–point temperature can produce a liquid water content (LWC) in the form of fine droplets, i. e., a supersaturated state.

Comparatively small temperature decreases in an airstream of moderate relative humidity can lead to high relative humidities or states of slight supersaturation. This is illustrated in Fig. 1 where the temperature decreases capable of producing humid air conditions with a potential threat to filter performance are plotted against air dry–bulb temperatures between approx. 10 and 100 °C. The curves are valid for standard atmospheric pressure and a given initial 70 % relative humidity (rh), a recommended maximum /7,8/ due to the occurence of capillary condensation /6/ in dust loaded filter media at higher humidities. Values used for the plots were calculated using humidity tables for moist air /9/ based upon the Mollier psychrometric chart /10/.

It can be seen for 20 °C that a decrease of 2 °C in the dry–bulb temperature is enough to raise the relative humidity up to 80 %, a condition sufficient to cause damage to the filter medium in aged, dust loaded filter units at design flow /6/. Should the same airflow be cooled by 6 °C, a slightly supersaturated state would exist at the resultant 14 °C. As a point of general reference, the LWC of this state corresponds to 0.1 g/m^3 (g H_2O per m^3 saturated air), the order of magnitude typical for a natural fog /11/.

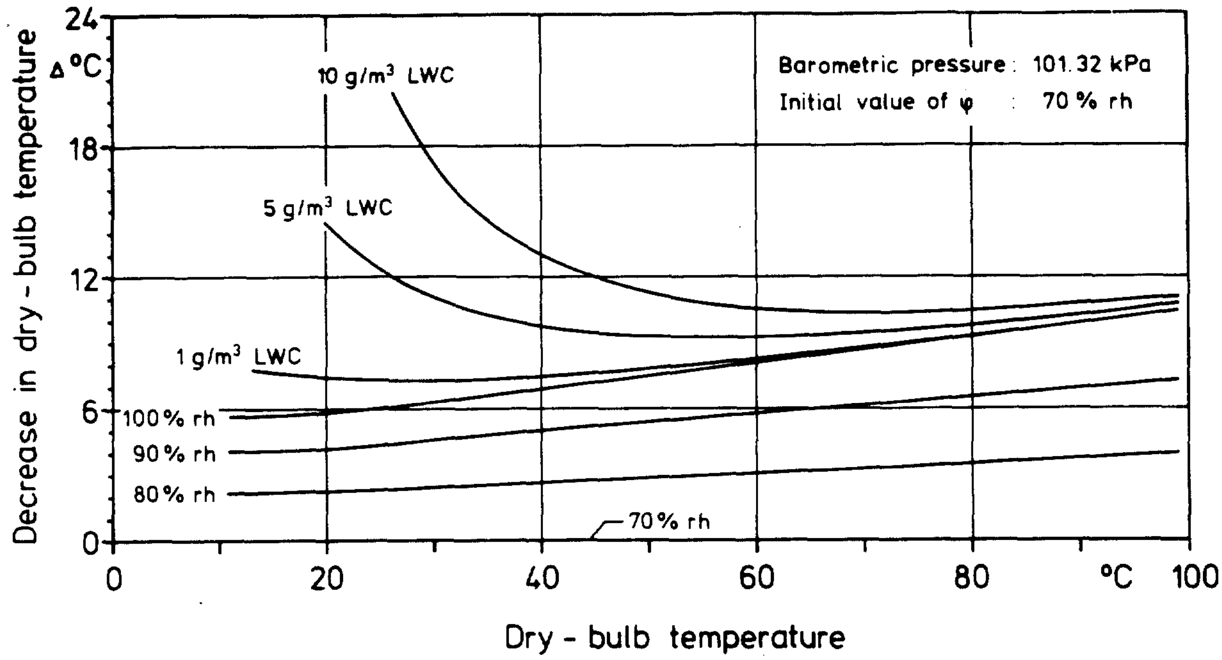


Fig. 1: Temperature Decreases Necessary to Produce Various States of Humidity for Air Initially at 70 % rh.

Airstreams with liquid water contents in the range above 1 g/m³ could most likely be expected to be caused by a major accident in a nuclear facility. Fog formation by water vapor condensation upstream of filters during a LOCA or a fire extinguishing proceedure would tend to be greatest at the time when the largest difference in temperature between the air-cleaning system components and the airstream exists. Which values of LWC might be involved or how they would vary with time is not yet established. With respect to a maximum possible LWC limited only by aerosol physics, a value as high as 40 g/m³ has been generated in a laboratory apparatus /12/.

Discounting containment spray system operation, the upper limit for the liquid water content in the air of a reactor containment building a short time after a LOCA would probably be restricted to several g/m³ due to agglomeration and the relatively rapid fallout of larger droplets /13/. Since the settling velocity is a function of the droplet diameter squared /14/, the droplet size distribution becomes an important factor in estimating the lifetime and behavior of a water aerosol.

Filter Failure in Humid Airflows

When the filter medium of a filter unit in an airstream suffers mechanical damage, with a resulting irreversible decrease in filtration efficiency to a value below specification requirements, filter failure can be said to have taken place. The quasi-static forces of the airstream apply so-called "mechanical" loads on the filter as a structure. The differential pressure (pressure drop) at which the folded filter medium will first tear and lose its integrity is referred to as the structural limit or the burst strength of the filter.

This characteristic offers one means for judging the ability of the filter medium to withstand the internal stresses from the mechanical loading on the filter pack and frame created by the airflow. In dry air the structural limit is determined by increasing the flow through the filter, significantly above the manufacturer's rated value, until the filter medium tears. Tests in humid air can be carried out at design flow with an air moisture content high enough to bring about failure within a reasonable exposure time. The structural limit can be defined to be the value of differential pressure below which the filter medium will remain intact and continue to function properly.

Similarly, the mechanical load acting on a filter at any given time can be represented by filter differential pressure, to which it is generally directly proportional. When in addition to the structural limit, the expected mechanical loads on a filter in an air cleaning system have been established, safety margins for the structural integrity of the filter medium can be calculated for filters under the expected conditions of operation.

The capability of filters to remain intact or to function correctly in humid airflows is limited principally by the effects of free moisture on the integrity and the flow resistance of the filter medium. In supersaturated airflows the primary process behind the incorporation of water into the filter medium is droplet interception by the fibers /15, 16/. The presence of liquid water in a filter medium has been established to have a number of adverse effects on filter performance characteristics /17, literature surveys in 6, 15 & 16/.

Variation in the mechanical loading at constant flow rate and in the structural strength of filters during exposure to humid airflows is depicted conceptually in Figure 2, for example. Both characteristics are represented here by filter differential pressure. Assumed is a constant high air humidity of > 80% rh for dust loaded filters or a LWC > 0.5 g/m^3 for new clean filters. These two minimum values of air humidity have been observed to be sufficient to bring typical nuclear grade commercial HEPA filters to the course of failure shown in Figure 2. Evident is a decrease in structural strength and a simultaneous increase in mechanical loading for filters in humid airflow.

Explanations for the decline in the structural limit include a significant reduction in filter medium tensile strength, and for deep-pleat filters, a loss of tightness in the filter pack. Contact and mechanical interaction between the edges of the aluminium separators and the ends of the pleats in the loosened pack also contribute to the decrease in structural strength /6, 18/.

In general the mechanical loading increases proportionally with the differential pressure, as a result of the increase in flow resistance due to the blockage of the air passageways in the filter medium by liquid water. Filter design, the degree of air humidity, and previously captured dust particles in the fiber matrix of the filter medium are factors known to most significantly influence the increase in flow resistance /19/.

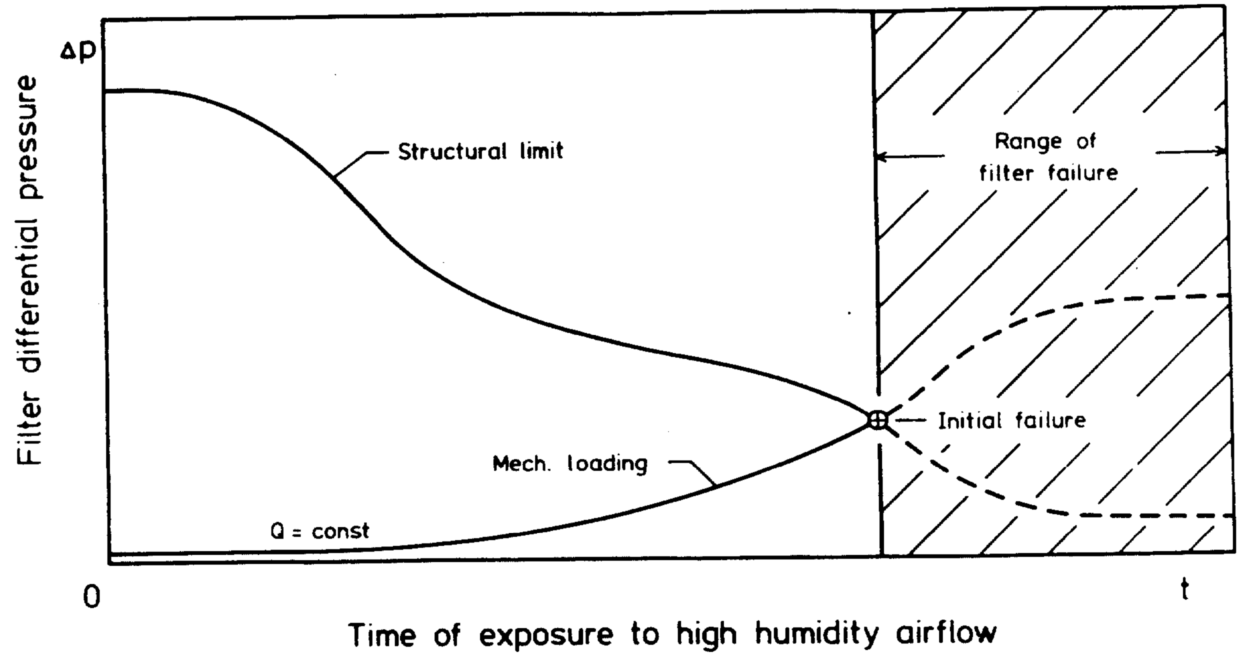


Fig. 2: The Variation of HEPA-Filter Mechanical Loading and Structural Limit During Exposure to High Humidity Airflows.

If the increase in mechanical loading and the decrease in structural strength become large enough that the two curves intersect, then structural failure will occur: possibly within a few minutes for aged dust loaded filters; after several hours with new clean ones. This worst-case consequence of filter exposure to high humidity airflow can be prevented by minimizing either the loss in strength or the increase in differential pressure; so as to keep the mechanical loading from nearing the structural limit. Various countermeasures exist which can partially accomplish one or both of these goals.

One important development was that of filter media with a high water repellency value. This reduced both the loss in tensile strength and the increase in flow resistance during moisture exposure. Another measure, the use of demisters and downstream heaters located upstream of HEPA-filter units, as in Standby Gas Treatment Systems (SGTS) /20/, serve to lower the humidity of the incoming airstream to a safe level. Significant though these countermeasures have proven to be, they are not without weak points and have not yet totally succeeded in eliminating reports of moisture related filter failure. Radiation exposure, aging, and dust loading for instance, can severely reduce the effectiveness of water repellency treatments. Heaters are often apparently designed to deal with a maximum air humidity of only 100% rh /20/ and have been known to malfunction /21/.

In a more recent, first reported application of a glass-fiber filter medium reinforced on one side with a closely woven scrim of coarser glass fibers (LYDALL Grade 3255 LW1) improved filter strength at elevated temperatures was attained /22/. The same filter medium, augmented with specially corrugated separators, has since been shown to also increase the structural limits of deep-pleat filters in dry and supersaturated airflows /23, 24/. The flow resistance increase of clean high strength filters in airstreams with a LWC of 5 g/m³ was found to be less than typical commercial units /19/. On the basis of strength alone, the new filter design shows promise of notable progress toward the elimination of structural failure caused by moisture. But even should this prove to be realizable, the problem of air-cleaning system failure resulting from filters becoming clogged with water would still remain to be solved.

Malfunction of Air Cleaning Systems in Humid Airflows

In this case, though the filter medium remains physically intact, the filter causes malfunction of the air cleaning system by restricting the airflow to a value less than that necessary to fulfill design specifications. Particularly in supersaturated airstreams, water can block the upstream surface or fill the pores of the glass fiber matrix to the point that filter flow resistance increases beyond the capability of the blowers to maintain the minimum required flow through the system.

This is illustrated schematically in Figure 3 by use of the characteristic curve of the blowers and that of the system flow resistance. Under normal conditions the intersection of these two curves, point 1, lies within the normal range of operation. If as a result of humid airflows, the pressure drop of the dust loaded HEPA filters increases by the amount Δp_F such that the system resistance characteristic shifts from 0–1 to 0–2, point 2 will become the new system operating point. If as indicated here, the flow at point 2 lies in the range below that of the specified minimum value, Q_{min}, insufficient airflow is available for air cleaning purposes. The resulting improper distribution of the subatmospheric pressures within the system poses the risk of a loss of confinement.

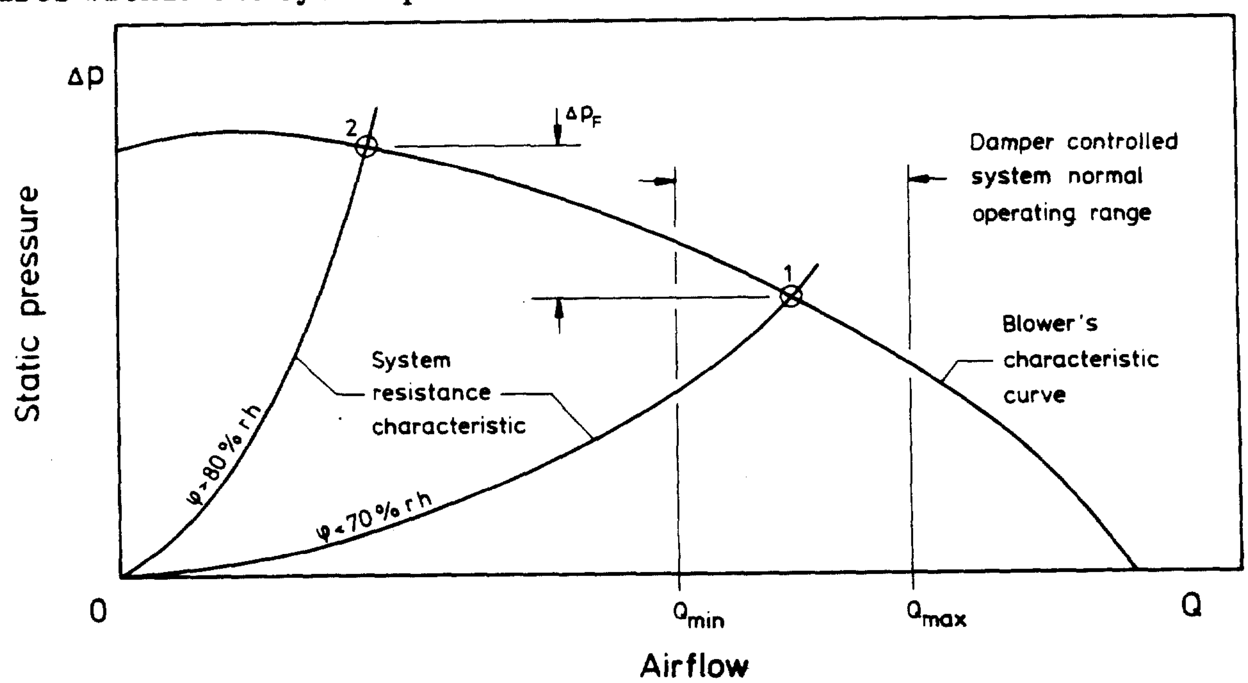


Fig. 3: Decrease in Air-Cleaning System Flow With Increase in Flow Resistance of Dust Loaded Filters Due to High Humidity.

The Significance of the Increase in Flow Resistance of HEPA Filters in Supersaturated Airflows

Airstreams with between 80 and 100% rh primarily threaten only dust loaded filters. At conditions above saturation, new clean filters also become subject to rapid deteriorations in performance. Due to the possibility that condensing water vapor could appear upstream of filter units during severe accident conditions, the subsequent effects on filter behavior need to be taken into consideration. The increase in flow resistance associated with supersaturated airstreams can lead to filter structural failure and air-cleaning system malfunction.

In this context there are a number of reasons for investigating the increase in filter flow resistance with respect to exposure time. The rate of increase can be used as an additional criterion in the evaluation and the specification of filter performance. Aspects of filter design or geometry which could be used to minimize the increase need to be identified and optimized. Moreover, changes in filter flow resistance as a function of time and airstream parameters are required as empirical input for computer modeling of flow and pressure transients in air cleaning systems.

II. Experimental Work

Objectives, Test Filters, Test Facility, Instrumentation, and Procedures

The influence of various filter and airstream parameters on filter flow resistance in supersaturated airstreams was investigated by testing some 120 nuclear-grade commercial HEPA filters of six different sizes from ten European manufacturers. The behavior of an additional thirty high-strength prototype filters from five manufacturers was also studied.

Test filters included some with metal frames for temperatures up to 250 °C and several mini-pleat types. However, principal interest centered on deep-pleat wooden frame units for service up to 130 °C, due to their inherently better structural stability. All filters tested had a water repellent filter medium of glass fiber: the clean and artificially loaded new filters as well as the dust loaded ones removed from routine service in the air cleaning system of a laboratory at Karlsruhe Nuclear Research Center (KfK) /6/.

The standard conditions for the majority of tests were 5 g/m³, 1700 m³/h, and 20 °C. Some tests also included liquid water contents of 0.6, 1.0, 2.5, and 10 g/m³, the maximum possible in the test facility. A number were also performed at other flow rates and temperatures. A few were also run with the filter pleats oriented horizontally instead of vertically. Filter behavior in vertical airstreams, for flow in the upward and in the downward direction, could also be investigated to some extent.

Tests were conducted in the test facility TAIFUN /25, 26/ located at KfK. As indicated schematically in Figure 4, the test filter was mounted in the 4th test position of the 1-m diameter test section. A metal fiber HEPA filter /27/ in test station 6 served as a guard to protect the blower from water droplets and debris released by test filters at failure. The airflow in the duct between the test section outlet and the inlet to the two-stage blower was kept at ambient atmospheric pressure as a reference for the flow measurement.

In the high pressure side of the system, the airflow can be directed from the blower discharge through a number of components for conditioning to the required temperature and relative humidity, before it enters the test section. A photo of the 10-m long test section, looking upstream from the test section outlet, is shown in Figure 5. To generate supersaturated conditions, up to 18 pneumatic atomizing nozzles spray a water aerosol into the airstream in the flow direction, 4.8 m upstream of the test filter. Condensate, fallout from the water aerosol, and runoff water from filters and droplet separators drain from outlets at the bottom of the test section.

During testing, steam was unfortunately not available and the air entered the test section at relative humidities as low as 66%, corresponding to a dry-bulb temperature 4 ^{0}C higher than the 20 ^{0}C at the test filter, for example. The water spray had to be depended upon to cool the air down to saturation at the test temperature as well as to supersaturate the airflow. Hence, obtaining reliably constant liquid water contents in the range between 0.6 and 2.5 g/m^3 was best accomplished by employing no less than 12 of the 18 nozzles and removing moisture in excess of the test value with the help of a wave-plate droplet separator in position 1. For LWCs above 2.5 up to 10 g/m^3 the droplet separator was removed.

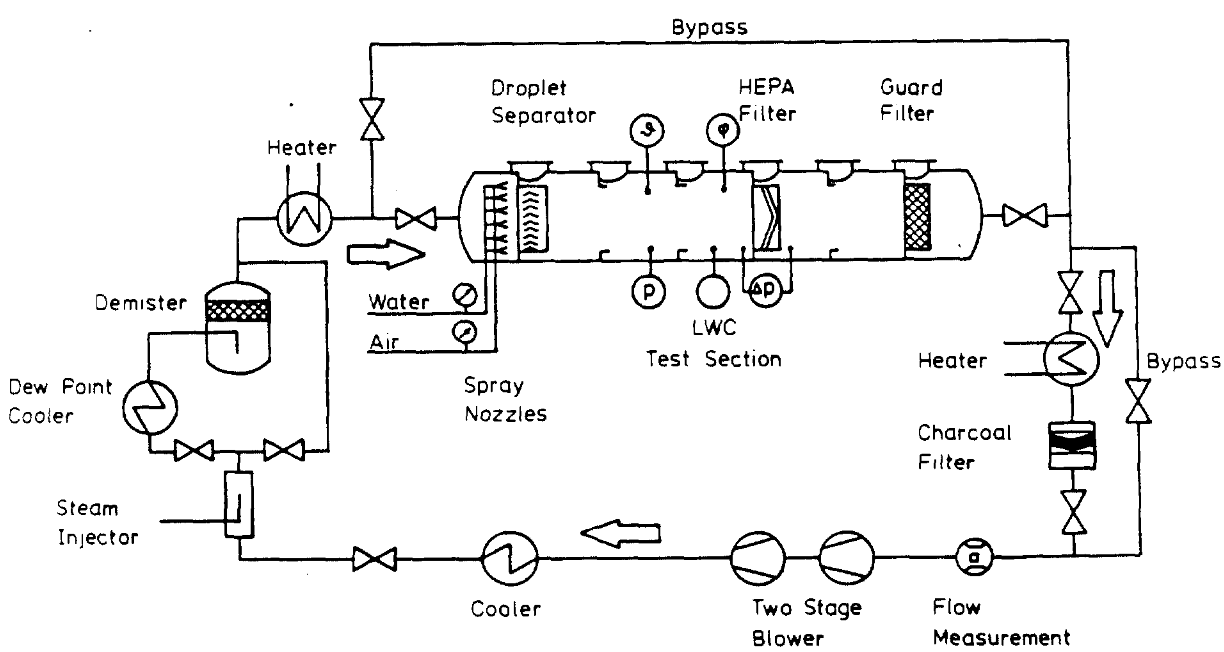


Fig. 4: Schematic of the Test Facility TAIFUN.

Airstream parameters measured just ahead of the test filter included: dry- and wet-bulb temperatures to an accuracy of ± 0.1 ^{0}C with calibrated 4-wire platinum resistance thermometers in an aspirated psychrometer (ADOLF THIES GmbH & Co., Mod. 1.1112.10), and pressures with variable reluctance transducers to an accuracy of ± 100 Pa. For higher accuracies of ± 10 Pa, a U-tube water manometer was also employed when necessary. The temperatures and filter pressure drop were registered with chart recorders. A mercury column barometer served for reading ambient atmospheric pressure.

After leaving the test section, the test air flowed to the flow measuring station via a bypass and finally back to the blower inlet. The airflow was measured with a vortex flow meter (YOKOGAWA Electrofact, Mod. YF100) to an accuracy of ± 20 m^3/h and regulated by way of electronic speed control of the blower motor. For tests in vertical airstreams a commercial filter housing /7/ (H. KRANTZ GmbH & Co., Nuclear Karlsruhe, Mod. VS) connected to the nozzle inspection port upstream of test station 1, served as a bypass to the test section which had been blocked off to airflow by a plate in test position 3.

Spray System Operation. The spray nozzles (SPRAYING SYSTEMS CO., Mod. No. 1/4 JSS) were consistently operated at a manifold pressure of 100 kPa with water flows of between 0.5 and 2.5 l/h per nozzle, depending upon airstream flow and LWC. The feed water was heated to 30 °C and maintained at a pressure of 200 kPa in the storage tank upstream of the manual flow control valve. Rotameters were used to measure the air and water flows to the nozzles. A photo of three of the nozzles taken during service is shown in Figure 6. Nozzle operation could be monitored visually through a plexiglass flange 0.5 m in diameter mounted on the side of the test section beside the ring shaped manifolds supporting the nozzles.

Despite water treatment and filtration, a partial and sometimes total clogging of several nozzles would frequently occur after some hours of operation. To prevent this from reducing the airstream LWC during tests, not all nozzles initially had access to feed water. From 4 to 6 nozzles at the top of the gravity-fed supply line were left in reserve and available to automatically take over for any that clogged. When a nozzle ceased spraying, the water level in the manifold would rise up to the level of the lowest reserve nozzle which would then begin operation. Only to attain 10 g/m^3 did it prove necessary to use all 18 nozzles simultaneously in tests which lasted less than 0.5 h. The nozzles had to be cleaned rather frequently, often on a daily basis.

Fig. 5: View Along the Side of the Test Section.

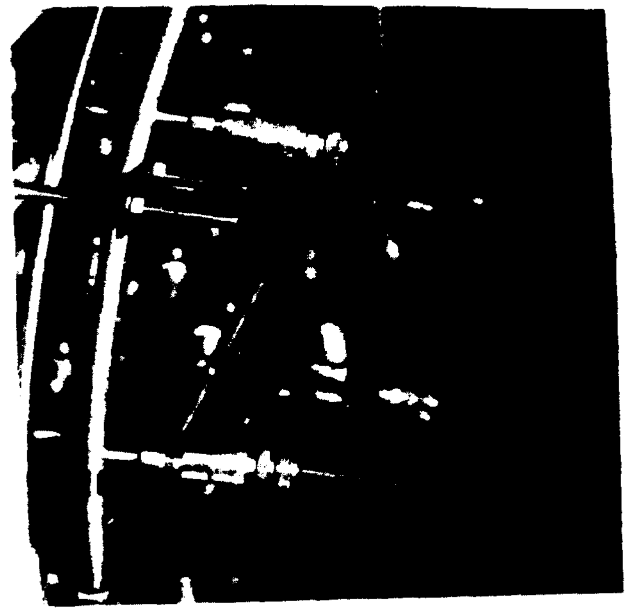


Fig. 6: Photo of Spray Nozzles During Operation.

Measurement of the Liquid Water Content of the Airstream. A discontinuous integral gravimetric method was selected as the simplest and most reliable means to measure the average liquid water content of the airstream. Commercial deep-pleat nuclear grade HEPA filters in the 610x610x292-mm size served as the sampling filters for this method. One important requirement for such filters is a high water holding capacity prior to incipient runoff from the droplet collecting upstream surface. Also desirable is a residual stability under wet conditions after repeated use involving up to some 50 wetting and drying cycles. Filters were dried by a reverse flow of air at 30 °C after measurements, in order to be used several times during the course of a testing day.

The best filters for this application turned out to be high strength units with a woven glass-fiber scrim bonded to one side of the filter medium. To delay surface runoff for as long as possible, the filters were installed so that the scrim was on the upstream side, i. e., in an orientation to the airflow opposite that in normal service.

The measuring procedure was begun by running the test rig up to steady-state conditions of temperature, flow, and humidity without a filter in the test position. The desired liquid water content had been initially set to an approximate value by adjusting the water flow through the nozzles to a level determined in previous tests. By shutting off the compressed air supply to the spray nozzles for approximately two minutes, the flow of water droplets could be stopped for long enough to quickly install a measuring filter in the test position. The airstream itself continued to flow uninterrupted through the test section. The nozzle air supply was then turned on again for a predetermined, measured time during which the water droplets of the airstream were collected by the filter. Filters, used only in an initially dry state, were carefully weighed before and after each measurement with an uncertainty of ± 0.5 g.

It was assumed that the entire liquid water content of the airstream was intercepted by the high efficiency filter medium during the measurement and that no water escaped as runoff from the filter. No fog was observed leaving the downstream side of measuring filters which were disposed of the first time any moisture was visually detected on the downstream side. When water was found to have run off from the filter medium upstream surface, the measurement was also considered to be invalid.

Through measurement of the flow, Q, the exposure time, t, and the mass of the water captured by the sampling filter, M_w, the average liquid water content of the airstream, LWC, can be calculated by

$$LWC = \frac{M_w}{Q \cdot t} \qquad (1)$$

Based on the experience gained during testing, the maximum amount of water a measuring filter could be expected to reliably and repeatedly collect without the risk of runoff was about 2.5 kg. Depending upon airflow and liquid water content, this limited measuring times to as little as 10 minutes in some cases. Times of 15 or 20 minutes were most common with 60 minutes considered to be a practical upper limit.

It normally required an iterative process of several measurements and adjustments in the LWC of the air prior to an actual test before the value sought could be attained. During both measurements and tests the water and air flow to the spray nozzles as well as the airstream temperature and flow rate were held constant. In general, tests were run until filter structural failure occurred or a time of 20 h had elapsed.

At the end of each test the LWC was measured again. The average of this value and the one obtained just prior to the test, was considered the most representative one. In almost no case did the two measurements differ from each other by more than 10%. The uncertainties /28, 29/ of the measurements were calculated to be no greater than 10% of the measured value in the range of LCWs between 0.5 and 10 g/m^3.

In order to at least qualitatively record the LWC during tests, an aspirated psychrometer outfitted with a heating element at the inlet /30/ sat in the bottom of the test section 0.5 m upstream of the test filter during testing. The humidity of the air entering the instrument could thus be reduced to a measurable value below 100% rh by heating the air and vaporizing the droplets. Though in principal this method could be used to quantitatively determine the LWC of the airstream, practical experience indicated that more development and calibration time than was available would have been required to achieve this.

III. Test Results

Characteristics of the Water Aerosol

Early in the test program the size distribution of the airstream water droplets was determined at the midpoint of the duct cross section in test position 4. Measurements under isokinetic conditions were made at an airflow of 1700 m^3/h and a LWC of 1 g/m^3 using a scattered–light particle size counting analyzer /31/ capable of detecting droplets with diameters in the range from about 2 to 100 μm. Sampling times lasted for 120 s. The results are shown in Figure 7 where the number and mass cumulative–less-than fractions /14, 32/ of the water droplets are plotted. The number fraction varies from some 2 to 20 μm with a number median diameter of 5 μm. Ninety–five percent of the droplets were found to have diameters < 10 μm. The mass median diameter is seen to be slightly greater than 7 μm. A value of 9.5×10^9 droplets/m^3 was established for the fog concentration.

With the given test conditions and assuming minimal agglomeration, it can be shown that due to settling no droplets with diameters > 50 μm could have reached the measuring probe. Other authors using cascade impactors have measured droplet sizes up to about 100 μm for the same nozzle type /33, 34/. The absence here of appreciable numbers of droplets in the range between 20 and 50 μm may be due to differences in the operating conditions of the test facilities or of the nozzles.

Due to settling and visible fluctuations in the fog concentration along the test section height and width, the droplets could not be considered to be uniformly distributed in time or space. This was a major reason for selecting an integral method to measure the LWC.

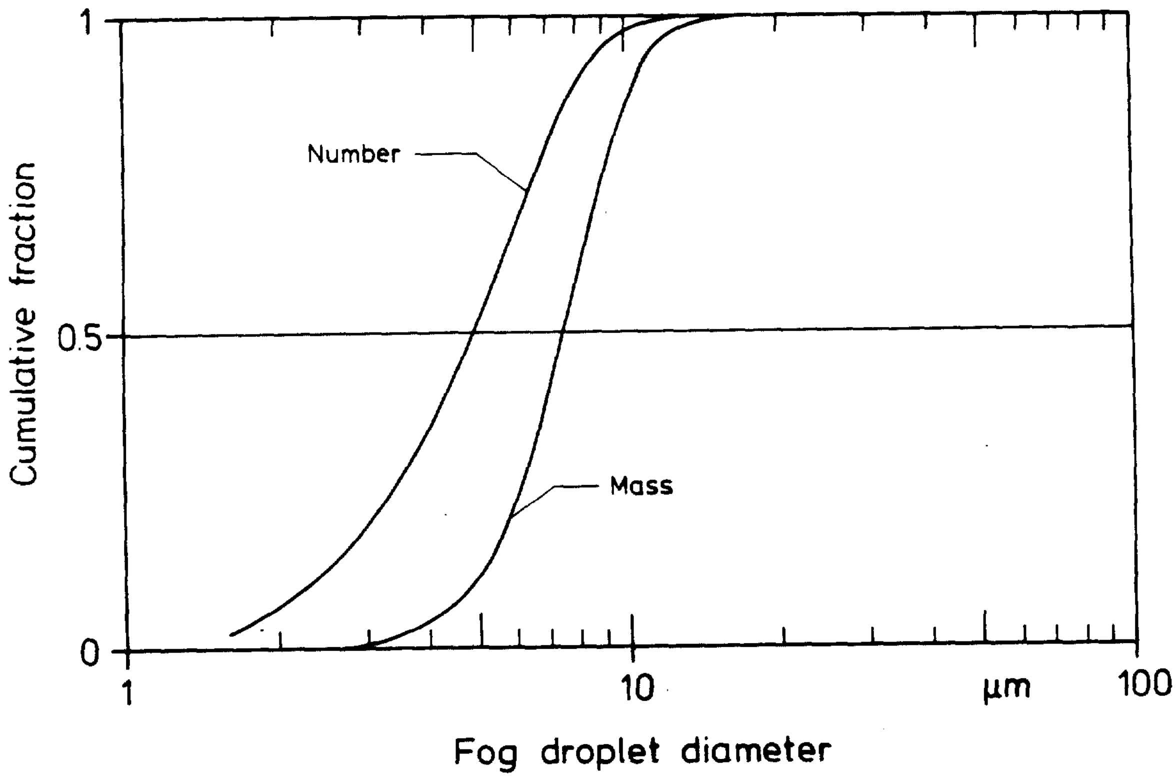


Fig. 7: Number and Mass Cumulative Frequencies of Water Droplets Measured at Test Station 4 in the Test Facility TAIFUN.

Increases in Filter Flow Resistance in Tests With Supersaturated Airstreams.

Filter Behavior During Tests. As with the sampling filters, the downstream face of test filters was visually monitored during tests. One characteristic observed with all filters, regardless of design, manufacturer or condition of loading, was the appearance of liquid water on the downstream side after some period of time. Depending primarily upon the water repellency of the filter medium and the state of supersaturation, small puddles or slow moving rivulets would generally appear on the horizontal surface of the adhesive at the bottom of the pleats between 10 and 60 min after the start of tests, at pressure drops between 0.3 and 1.5 kPa. In a few cases water drops were first observed falling from the edges of the separators up to 100 mm above the bottom of the pleats, presumably the result of pinholes or small local damages in the filter medium.

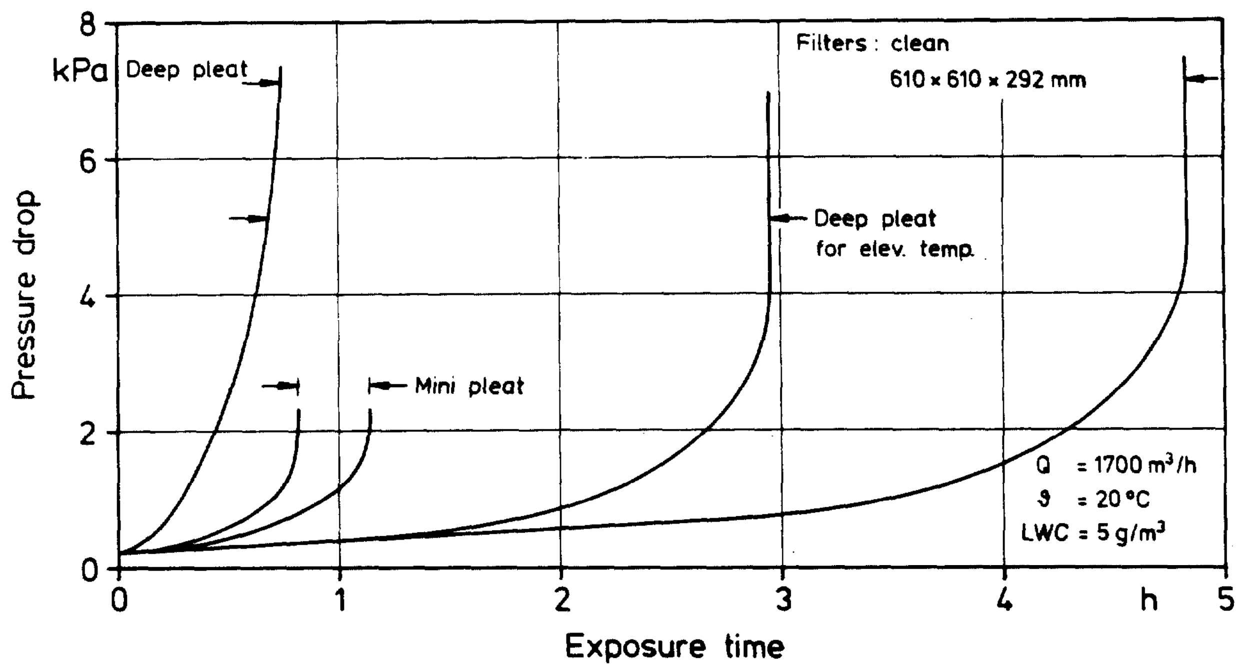
In the next phase of behavior for clean deep-pleat filters, runoff water appeared on the ends of the pleats followed by sprays of droplets emenating from the pleat ends and the triangular channels formed by filter medium and separators. This process usually began within some 100 mm from the bottom of the filter and spread upward to the top of the pleats in some 10 to 60 min. Based on visual observations, the diameters of these filter generated droplets were estimated to lie in the range of several hundred to several thousand μm. Droplets produced by the atomizing nozzles were visible on the downstream side of filters only after severe damage or in tests of low efficiency filters. Foam consisting of several layers of bubbles some 2 – 5 mm in diameter formed on the downstream side of filters from a few manufacturers for up to several hours.

One characteristic of the second phase in most tests was a transition from a uniform to a nonuniform velocity distribution in the air leaving the filter. In traverses made from the bottom to the top of the filter, the velocity tended to increase. The distribution across the filter width also exhibited random local fluctuation but with no clear trend. These observations also revealed some areas where no airflow at all was evident. The changes in velocity distribution correlated in most cases with an initial linear increase in filter pressure drop up to between roughly 0.5 to 1.0 kPa. The clogging of the filter medium from bottom to top is assumed to be the result of the drainage of water from top to bottom. Random localized areas with little or no airflow are probably related to the loosening of the filter pack which is typical for operation under high humidities /6/.

Following the transition phase, the steepest increase in the pressure drop coincided in time with the resulting velocity distributions in which most of the flow exited the filter within some 100 mm of the top of the pleats. The air velocity in the area below was approx. an order of magnitude smaller. This is considered the third and final stage in the course of the increase in filter differential pressure in clean deep-pleat filters. Dust loaded filters generally did not exhibit nonuniform distributions in the exit air velocity during tests. The pressure drop usually increased up to the point of structural failure so quickly that no significant drainage could occur.

The Effects of Various Parameters on Filter Flow Resistance. The effect of filter design on the increase in filter flow resistance is illustrated in Figure 8. The results from twenty standard deep–pleat filters from five manufacturers are summarized. These included four filters with metal frames for use at elevated temperature, each from a different manufacturer. Results for two of three high capacity deep–pleat types with wooden frame and design flow of 2500 m^3/h fall within the range of 0.75 to 4.8 h. The pressure drop of the third rose to 7 kPa in 11 h. The standard mini–pleat type is represented by tests of two filters from separate sources. Differential pressures of high capacity mini–pleat filters of 3000–m^3/h design flow from three other manufacturers increased to 2.5 kPa in 1.1, 2.5, and 4.2 h, respectively.

Based on earlier tests with similar filter units, the rather wide variation in the results within design groups can primarily be attributed to differences in the water repellency of the filter media involved. Water repellency measurements are planned for the filters tested. The elongation and stiffness properties of the filter medium may also play a role in the case of deep–pleat filters where deformation of the pleats along the peaks of the separator corrugations can decrease the surface area available for air flow. The rather poor performance of the mini–pleat units is explained by the weak panels of filter medium which deform and close off to air flow at relatively low pressure drops, especially at high humidity.



<u>Fig. 8:</u> Ranges of Increase in Flow Resistance of Three Filter Designs at Rated Flow, 20 °C, and 5 g/m^3.

The influence of the airstream average liquid water content on the increase in flow resistance of clean filters from two manufacturers can be seen in Figures 9 and 10. The curves of the CN type in the range of 1 to 5 g/m^3 show initially linear, moderate slopes followed by steep increases in Δp at the end of the test. The extreme slopes indicate a widespread blockage of the pores in the filter medium with water. An additional factor in this case was the relatively pliable filter medium which deformed over the peaks of the separator corrugations with increasing Δp. The results of most clean filters tested showed this general curve shape, usually with a less extreme steepness at the end prior to structural failure. Test results for the CN filters formed the boundary of 4.8 h in Figure 8.

The curves of the VP type filters from a second manufacturer exhibit more of an S shape than those of the CN type. The steepest part is followed by a gradual decay in slope toward the end of the test. The curves leave the impression that were it not for structural failure, an equilibrium state might have been reached. The S shaped curves were typical for clean deep-pleat filters with wooden frames from only two of the five manufacturers tested. They helped establish the left boundary of the range for deep-pleat filters in Figure 8 indicating that a low water repellency value may be responsible. Pending proof via actual measurements, further support for this hypothesis is provided by the results for dust loaded filters as illustrated in Figures 11 and 12. Decreases of 20 to 80% due to dust loading in service have been established for similar filters tested earlier /6/.

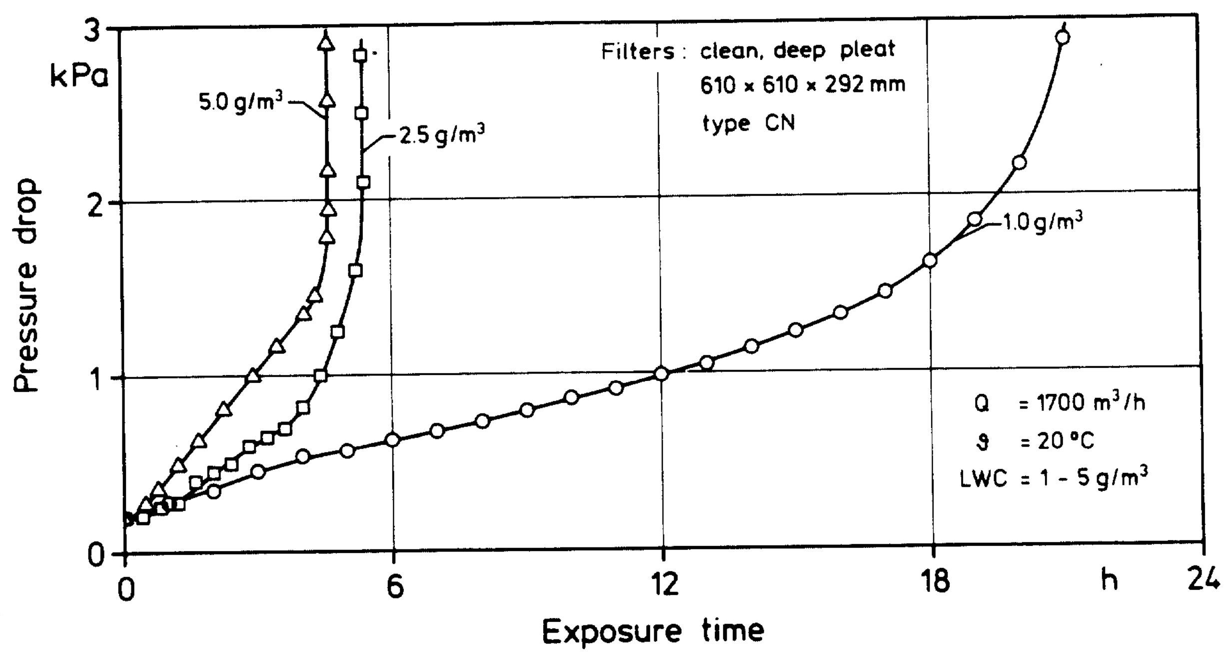


Fig. 9: Influence of the Air LWC on the Increase in Flow Resistance of Clean CN Type Filter Units at Rated Flow and 20 °C.

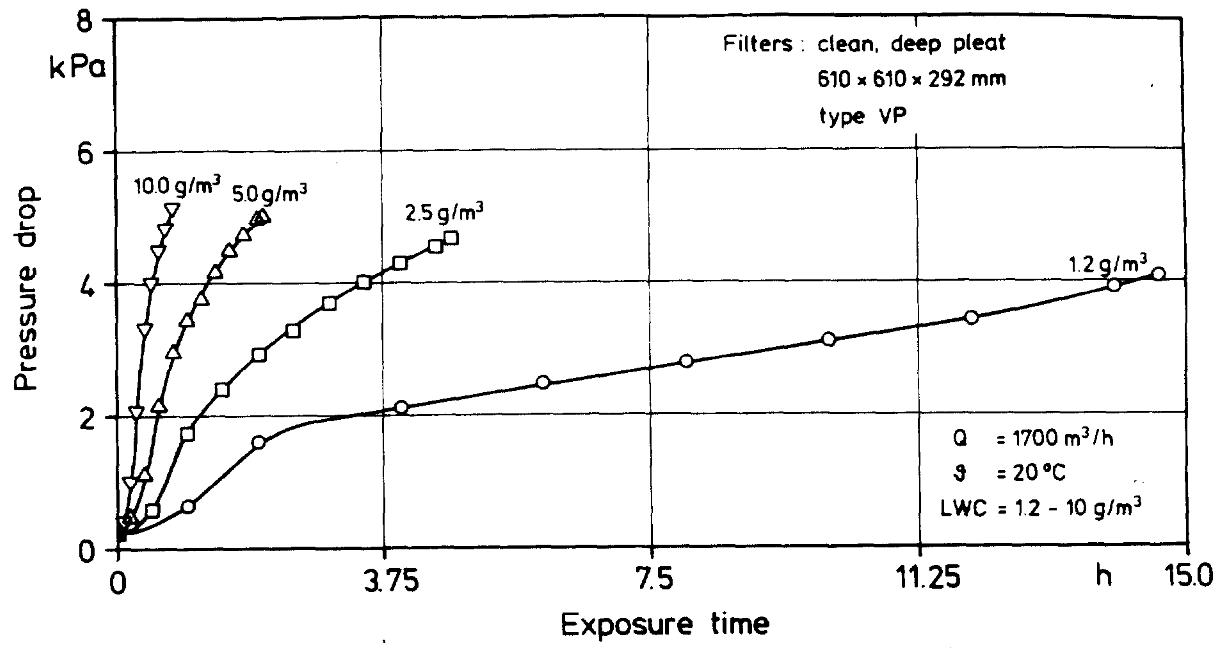


Fig. 10: **Influence of the Air LWC on the Increase in Flow Resistance of Clean VP Type Filter Units at Rated Flow and 20 °C.**

The curves for the slightly loaded CN type filters have shapes somewhat different from those of Figure 9. The extreme steepness at the end of the test is not evident as for clean CN type filters. More significant is the net result of the dust loading, namely the decrease in exposure times at which Δps large enough to cause filter failure or air–cleaning system malfunction are attained. Depending on the air LWC, the time elapsed in reaching a Δp of 3 kPa was reduced by factors of 15 to 30 due to only slight loadings of dust. The pressure drops of the three filters of Figure 11 after actual service lay between 270 and 370 Pa before testing.

The filters represented in Figure 12 were loaded in service with dust up to pressure drops between 850 and 1100 Pa. The decrease in the slope of the curves after the initial steep rise in Δp is more evident here than for the slightly loaded filters. The rate of increase up to 3 kPa at the LWC of 5 g/m³ is four times greater than that for the slightly loaded filter of Figure 11. The Δp for the filter tested at less than 100% rh almost reached an equilibrium condition before structural failure occurred. This provides an idea as to how the flow resistance of dust loaded filters with higher structural limits might increase with longer exposure to supersaturated airflows.

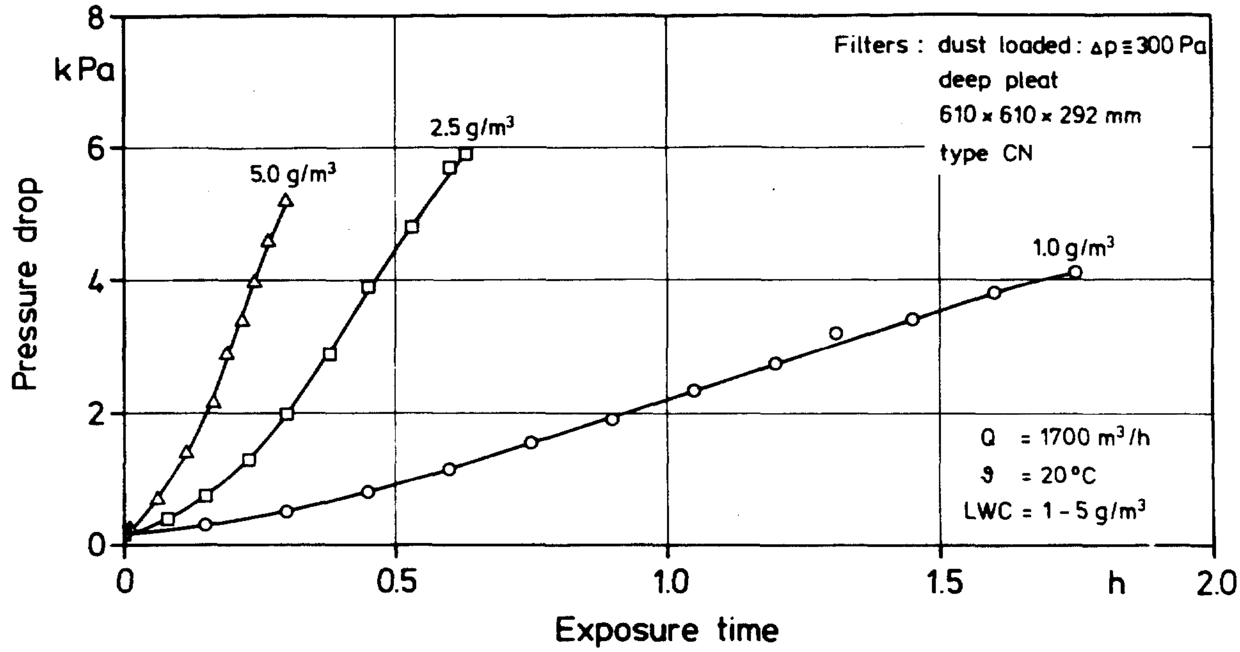


Fig. 11: Influence of Air LWC on the Increase in Flow Resistance of Lightly Loaded CN Type Filters at Rated Flow and 20 °C.

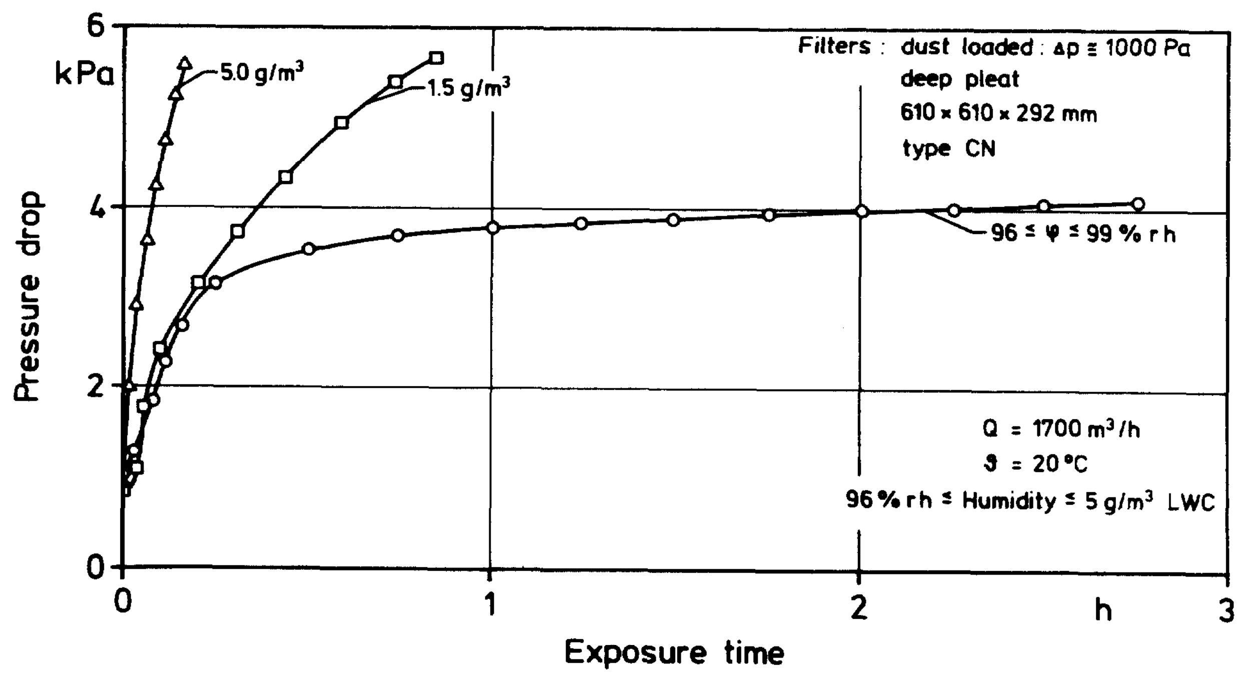


Fig. 12: Influence of Air Humidity on the Increase in Flow Resistance of Heavily Loaded CN Type Filters at Rated Flow and 20 °C.

Another factor found to influence the flow resistance of clean filters in supersaturated airstreams is the direction of airflow. An example is illustrated by the three curves to the right in Figure 13. The dashed line for a clean filter with vertically oriented pleats in a horizontal airflow was liberally extrapolated from test results for 5 g/m³ such that there is no question that the time to maximum Δp could not be greater than the 4 h indicated. The two curves to the right of the dashed one represent results for clean filters in vertical airstreams, one with the flow direction upward (l), the other downward (r).

Both filters in the vertical airstream at rated flow and 2.5 g/m³ show at least some advantage over the one in the horizontal airflow. Results (not shown) from similar filter tests confirm the relative relationship of the three plots. The Δp increase of the filter in the downward flow airstream was limited to 1 kPa after 12 h. This was attributed to the improved drainage of water from the filter medium in this configuration. Unfortunately however, the runoff water drains only from the downstream side of the filter. The differences among the results for clean filters under the various flow conditions were on the order of hours. Those separating filters slightly loaded with dust were only on the order of minutes, as seen from the three curves at the left of Figure 13.

The orientation of the filter pleats in horizontal airflows also proved to affect the increase in filter differential pressure (not shown). In clean standard commercial units, the rate of Δp increase for pleats oriented horizontally was almost always greater than for vertically oriented ones. Just the opposite was true for clean high strength filter units, for reasons that are not yet understood. It is to be expected that the influence of dust loading would also counteract the advantage to be gained by this improvement.

Shown in Figure 14 is a comparison of the Δp increase for clean standard commercial filters and high strength units, both types with deep pleats vertically oriented in horizontal airstreams at rated flow and 5 g/m³ /19/. Represented are the results for nine high strength filters from three manufacturers and the filters as described for Figure 8. After 20 h of exposure the pressure drop of the high strength filters had increased to between 4.4 and 6.8 kPa without failure or having reached an equilibrium value. The Δps of the standard filters had increased to values between roughly 3.5 and 9 kPa at structural failure within 4.8 h. The smaller Δp increase of the high strength filters is due to improved stability which prevents loosening of the filter pack, an increased stiffness in the filter medium which limits deformations, and better drainage of captured water via the inclined corrugations of the separators. The nonuniform distributions in the velocity of air exiting the high strength filters were not so pronounced as in the standard filter units.

Results of some preliminary tests (not shown) indicated that filters loaded with particles of soot or activated charcoal fines from iodine adsorption filters, behaved more like clean filters than units loaded with fine particle dusts in service. This indicates that not all types of particulate loadings will necessarily reduce the water repellency of HEPA-filter media equally.

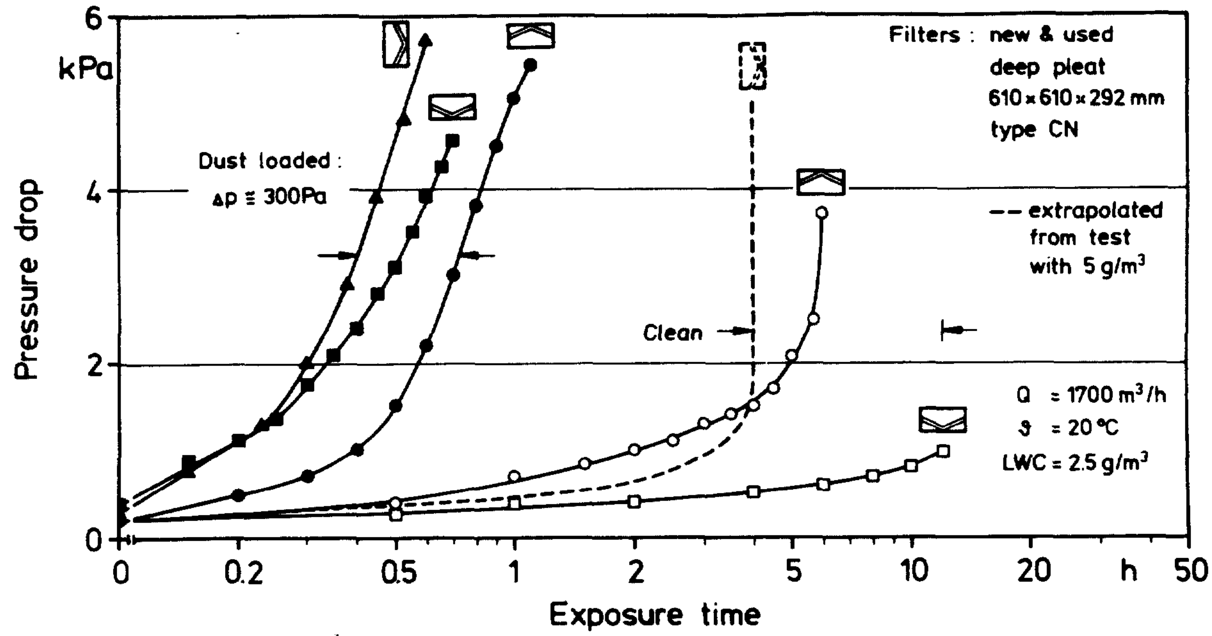


Fig. 13: Influence of Flow Direction on Increase in Flow Resistance of CN Type Filter Units at Rated Flow, 20 °C, and 2.5 g/m³.

Large differences in the rate of Δp increases with the dates of filter production were noted for clean filters from most manufacturers. Success in parametric studies of the behavior of clean filters is judged to depend heavily upon having a sufficient quantity of filter units from the same production lot. The scatter in results for dust loaded filters varied correspondingly very little, once more emphasizing the dominant influence of dust loading on the Δp increase.

Tests at temperatures up to 50 °C indicated in most cases that increasing temperature accelerated the rate of pressure drop increase only slightly for both clean and loaded filters. That water droplets may not necessarily be intercepted uniformly along the pleat depth was one implication of results from preliminary tests (not shown) with clean filters of several depths at various superficial velocities up to values corresponding to two times design flow.

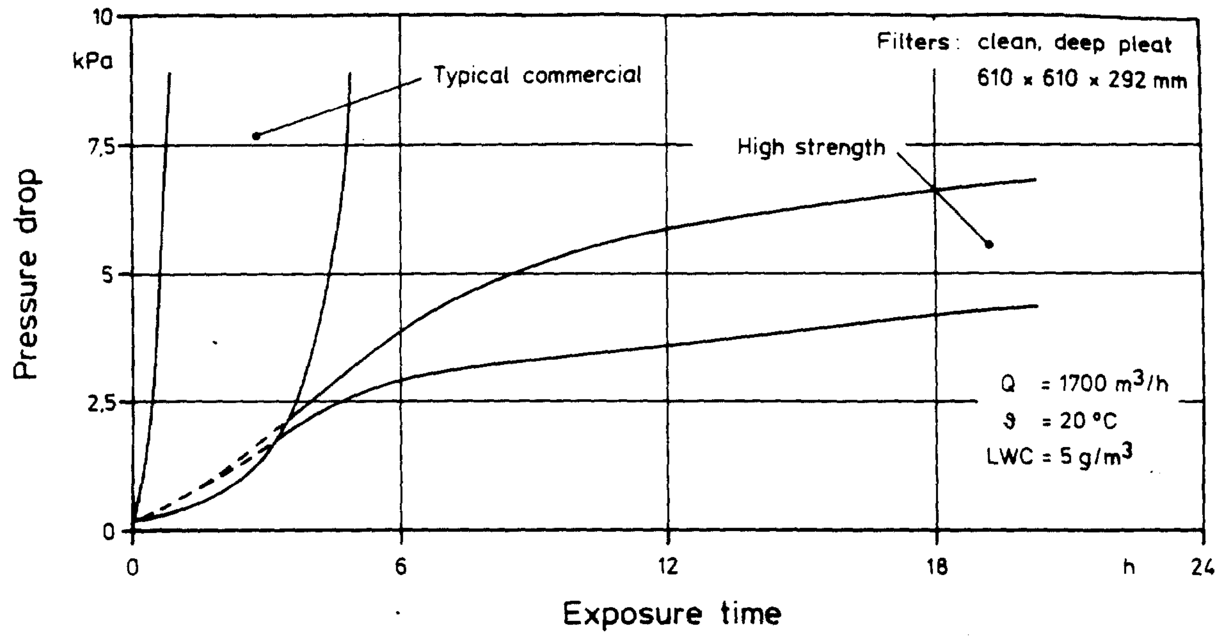


Fig. 14: **Ranges of Increase in Flow Resistance of Standard and High Strength Filter Units at Rated Flow, 20 °C, and 5 g/m³ /19/.**

IV. Conclusions

The test results show thaւ ւne rate and the extent of pressure drop increase for typical clean commercial filters at rated flow in supersaturated airstreams can vary appreciably with the filter design and manufacturer as well as with the air humidity. The susceptibility of clean filters to such increases can be reduced by changes in filter design or pleat orientation to the airflow that enhance the drainage of water from the filter medium. However, the effectiveness of the improvements studied so far appears to be counteracted by even small loadings of fine dust in the filter medium. Any success in reducing the sensitivity of dust loaded filters to fog related increases in pressure drop will have to result from an increase in the surface water repellency of the dust loaded filter medium.

The rather rapid penetration of water through filters by seepage indicates that in applications where water soluble radioactive salts are involved, a loss of containment could occur under fog conditions without any structural damage to the filter units. And despite their high removal efficiencies, intact HEPA filters can be depended upon for only short periods to prevent the partial reentrainment of captured water; in the form of secondary droplets generated on the downstream surface of the filter medium.

The implementation of a method to quantitatively measure the average liquid water content of airstreams helped make it possible to evaluate filter performance and to establish the existence of reductions in the flow resistance of clean filters in supersaturated airflows. A contribution toward obtaining the quantitative empirical data required for computer modeling of flow dynamics in air cleaning systems was also achieved.

V. Acknowledgements

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VI. References

/1/ Gilbert, H.
The high-efficiency filter in nuclear air cleaning;
CONF-860 820 (1987), p. 933 ff.

/2/ First, M.W.; Gilbert, H.
Aerosol filtration;
Nuclear Safety, 23 (2) (1982), p. 167 ff.

/3/ First, M.W.
Trends in the design and operation of off-gas cleaning systems in nuclear facilities;
in: Management of Wastes from Nuclear Facilities
STI/PUB/561, ISBN 92-0-020380-9,
IAEA, Vienna 1980, p. 3 ff.

/4/ Linder, P.
Air filters for use at nuclear facilities;
STI/DOC//10/122
IAEA, Vienna 1970.

/5/ Carbaugh, E.H.
A survey of HEPA filter experience;
CONF-820 833 (1983), p. 790 ff.

/6/ Ricketts, C.I.; Ruedinger, V.; Wilhelm, J.G.
HEPA-filter behavior under high humidity airflows;
CONF-860 820 (1987), p. 319 ff.

/7/ Ohlmeyer, M.; Stotz, W.
Aerosol filtration systems for the exhaust air from nuclear engineering facilities;
Kerntechnik 15 (9) (1973), p. 416 ff.

/8/ Goumondy, J.P. et al.
Retention des gaz et aerosols radioactifs dans les effluents humides du retraitement;
in: Management of Gaseous Wastes from Nuclear Facilities
STI/PUB/561, ISBN 92-0-020380-9
IAEA, Vienna 1980, p. 557 ff.

/9/ Heraeus-Voetsch GmbH
Heraeus-Voetsch Feuchtetabelle; Copyright 1980
D-7460 Balingen 14, FRG.

/10/ Threlkeld, J.L.
Thermal environmental engineering; 2nd edition,
Prentice-Hall Inc., Englewood Cliffs, NJ 1970.

/11/ Juisto, J.E.
Fog structure;
in: Clouds: their formation, optical properties, and effects;
edited by: P.V. Hoobs
Academic Press Inc., New York 1981, p. 187 ff.

/12/ Mallant, R.K.A.M.
The use of laboratory generated fog for testing fog water collectors, cloud chemistry experiments and effect studies;
in: Aerosols: formation and reactivity;
Proc. 2nd Int. Aerosol Conf., Berlin 1986
Pergamon Journals Ltd., London 1986, p.71 ff.

/13/ Bunz, H.
Private communication
KfK, July 1988.

/14/ Loeffler, F.; Dietrich, H.; Flatt, W.
Staubabscheidung mit Schlauchfiltern und Taschenfiltern;
Verlag Friedr. Vieweg & Sohn,
Braunschweig/Wiesbaden, FRG, 1984.

/15/ Ruedinger, V.; Ricketts, C.I.; Wilhelm, J.G.
Zum Verhalten von Schwebstoffiltern der Klasse S bei Einwirkung hoher Luftfeuchte;
in: Filter für kerntechnische Anlagen;
BMI-1985-099, ISSN 0724-3316 (1985)
FIZ Karlsruhe, D-7514 Eggenstein 2, FRG.

/16/ Ruedinger, V.; Ricketts, C.I.; Wilhelm, J.G.
Limits of HEPA-filter application under high humidity conditions;
CONF-840 806 (1985), p. 1058 ff.

/17/ Normann, B.
The effects of high relative humidities on HEPA filter media;
CONF-860 820 (1987), p. 300 ff.

/18/ Ruedinger, V.; Ricketts, C.I.; Wilhelm, J.G.
Development of glass-fiber HEPA filters of high structural strength on the basis of the establishment of the failure mechanisms;
CONF-860 820 (1987) p. 947 ff.

/19/ Ruedinger, V. et al.
Schwebstoffilterung unter Störfallbedingungen;
in: Projekt Reaktor Sicherheit, Jahresbericht 1987
KfK 4450/87 (1988) p. 4400/199 ff.

/20/ Zavadoski, R.
Background information for USAEC regulatory guide 1.52;
in: Proc. of Seminar on Iodine Filter Testing;
Karlsruhe, FRG, December 1973
Commission of the European Communities, Doc. V/559/74,
Luxembourg (1974), p. 547 ff.

/21/ Moeller, D.W.
Current challenges in air cleaning at nuclear facilities;
Nuclear Safety 18 (5) (1977), p. 633 ff.

/22/ Pratt, R.P.
The performance of filters under hot dynamic conditions;
in: Gaseous Effluent Treatment in Nuclear Installations,
ed. by: G.Fraser & L.Luykx, CEC, EUR 10580
Graham & Trotman, London 1986, p. 824 ff.

/23/ Ruedinger, V.; Ricketts, C.I.; Wilhelm, J.G.
Schwebstoffilter hoher mechanischer Belastbarkeit;
ATW 32 (12) (1987), p. 587 ff.

/24/ Ruedinger, V.; Ricketts, C.I.; Wilhelm, J.G.
The realization of commercial high-strength HEPA filters;
in: Proceedings of the 20th DOE Air Cleaning Conference
Boston, MA, Aug. 1988, to be published in 1989.

/25/ Dillmann, H.-G.; Bruederle, F.; Wilhelm, J.G.
Der technische Filterpruefstand in Karlsruhe;
in: Proc. of Seminar on Iodine Filter Testing;
Karlsruhe, FRG, December 1973
Commission of the European Communities, Doc. V/559/74,
Luxembourg (1974), p. 353 ff.

/26/ Wilhelm, J.G.; Dillmann, H.-G.; Gerlach, K.
Testing of iodine filter systems under normal and post-accident conditions;
CONF-720 823 (1972), p. 434 ff.

/27/ Dillmann, H.-G.; Pasler, H.
A containment-venting filter concept and its implementation with stainless-steel fiber filters;
in: Proc. of 5th International Meeting on Thermal Nuclear Reactor Safety; Karlsruhe, FRG, September 1984
KfK 3880 (1984), p. 1593 ff.

/28/ Kline, S.J.; McClintock, F.A.
Describing uncertainties in single-sample experiments;
Mech. Eng., (January 1953), p. 3 ff.

/29/ DIN 1319 Blatt 3: 1.72
Grundbegriffe der Meßtechnik
Beuth-Vertrieb GmbH, Berlin 1972.

/30/ Branton, C.I.
A proposed technique for measuring relative humidity at below freezing temperatures;
in: Humidity and Moisture, ed. by: A.Wexler
Proc. Int. Symp. on Humidity and Moisture, Washington, DC
Reinhold Pub. Corp., New York 1965, p. 95 ff.

/31/ Schegk, C.-D.; Umhauer, H.; Loeffler, F.
Messen von Tropfengroeßenverteilungen mit Hilfe eines Streulicht-Partikelgroeßen-Zaehlanalysators;
Staub-Reinhaltung der Luft 44 (6) (1984), p. 263 ff.

/32/ Licht, W.
Air pollution control engineering;
Marcel Dekker Inc., New York 1980.

/33/ First, M.W.; Leith, D.H.
ACS entrainment separator performance for small droplet-air-steam service;
Report No. ACS-1, ACS Industries Inc., Woonsocket, RI 1975.

/34/ Griwatz, G.H.; Friel, J.V.; Bicehouse, J.L.
Moisture separators for fine (1-10 μm) water-air-steam service: their performance, development and status;
MSAR 71-45 MSA Research Corp.
Evans City, PA 1971.

DISCUSSION

KOVACH, J. L.: For practical purposes, very few air cleaning systems have fan static pressures capable of putting filters under the stress that you are showing here. Unfortunately, in some cases we can barely get clean air through at lower pressures, not to talk about having the ability to go to this high pressure drop. Maybe some of the bad calculations made by some of our architect-engineering firms in sizing fans were beneficial to prevent failure of the HEPA filters.

RICKETTS: I would not entirely agree. We ran the tests at constant air flow up to rather high differential pressures; admittedly higher than one would normally be able to attain in an air cleaning system. However, we did that in order to have a standard basis upon which to evaluate and compare filter performance. There would be a problem in an air cleaning system should the filters become clogged with water. This would reduce the air flow to such an extent that the air cleaning process would no longer meet system design specifications despite the filters remaining intact.

WILHELM: In a power reactor station with a water cooled reactor, one can imagine that a tube breaks and you get steam in a room which is directly connected to an air cleaning system. If pressure in the room increases you will develop pressure in the connected air cleaning system. At the same time, you challenge the filter with water. That is, exactly, one of the situations we are looking at. Other situations come from operations other than at the reactor, such as reprocessing. We found high pressure differentials on filters, especially when the filters got wet by just dropping the temperature to below the dew point, as may happen in power stations. One example is a power station in the far north of Europe where the ducts run through the cool outside air with a temperature of more than 30 degrees below zero. This is an extreme example but it is not too extreme to mention with a major break in a water cooled reactor. This is one of the reasons the work was done.

KOVACH, J. L.: Do you think that this work will now convince our European colleagues to follow the good American example and put moisture separators into their air cleaning systems?

WILHELM: If you believe that the HEPA filters will be challenged by extreme conditions, the procedure now is to protect the HEPA filters from the atmosphere to be cleaned. Therefore, we dry the atmosphere, we condense the water, we heat up the atmosphere again, we have a pressure wall for when we have to expect a higher pressure differential, and so on. Most of the measures require energy and it is not inconceivable to think about developing filters that can withstand those challenges in the first place.

HYDER: What was the mass loading of dust and soot on the filters in g/m^2?

RICKETTS: For filters loaded with dust in normal service to pressure drops of between 300 and 1000 Pa at 1700 m^3/h and less than 70% RH, the mass loadings were established to lie in the range of 5 to 20 g/m^2. Correspondingly, the values for soot-loaded filters, as measured at an air relative humidity of about 60%, were 5 to 30 g/m^2 for pressure drops of 750 to 1400 Pa. These figures don't account for the higher water content of the soot, present during the artificial loading of the filters with the combustion products of oil or electrical cable insulation fires. Values reflecting the additional adsorbed moisture at the higher air relative humidities during loading could have been higher by as much as 50% for the mass loadings and 10% for the pressure drops.

BERGMAN: Do you agree with the proposition that structural failure in HEPA filters is primarily due to water clogging? Three examples support this proposition: (1) dust deposits cause earlier HEPA failure than soot deposits because dust absorbs more water than soot; (2) aged HEPA filters are destroyed easier than new HEPA filters primarily due to the lack of chemicals that prevent water absorption and (3) increased water challenge causes earlier HEPA failure.

RICKETTS: We would agree that the clogging of filters with water is one of two phenomena which contribute to filter structural failure in high humidity airflows. The blockage of the filter medium pores with water leads to an increase in pressure drop which results in higher mechanical loads on the filter pack at a given airflow. Additionally however, the presence of liquid water in the filter medium, even in quantities much less than that required to produce a clogged condition, will severely reduce the structural strength of the filter pack. Thus the structural load on the pack increases at the same time that the pack strength decreases. As measured by the filter pressure drop, the decrease in strength generally seems to be a factor of two to four times greater than the increase in mechanical loading at failure. Decreases in filter medium water repellency due to aging and dust loading, as you point out, accelerate the incorporation of water from supersaturated airstreams into the fiber matrix and consequently increase the moisture's adverse effects. And as you suggest, there appears to be a correlation between higher air humidities and shorter exposure times prior to failure. It is also evident that the pressure drop at which failure will occur tends to decrease with longer durations of exposure to humid airflow.

KOVACH, J. L.: Most U.S. air cleaning systems would not be able to raise the pressure drop through the HEPA bank to reach a failure; they would stop airflow. A typical rise is from 1" to 2" w.g. Will this type of data convince European colleagues to use demisters?

RICKETTS: Your question raises several important points. We agree that the test results presented here involve filter pressure drops greater than those which could be generated by the blowers in a typical nuclear air cleaning system. According to the Nuclear Air Cleaning Handbook, however, filters in U.S. facilities are routinely loaded with dust up to 4-5 in.w.g. (1000 - 1250 Pa), somewhat higher than figures of 1-2 in.w.g. As a result of humidity effects, the filters could become the air cleaning system components with the greatest flow resistance. Should the pressure drop across them increase enough to cause a decrease in flow, an additional increase of several inches water gauge must be allowed for, despite the reduced airflow. This would result not only because of the blower's characteristic curve but also from the fact that the sum of the decreases in pressure drop of other components, due to the lower flow, would become available to appear as an increase at the filters. It was also taken into consideration that higher than fan-generated pressure drops could result from expanding steam released during a LOCA. Although filter failure due to high humidity airflow was not the objective of the tests reported on here, in our opinion it still remains a serious problem, even in so-called normal operations that involve exposure to high air humidity. The report from Mr. Carbaugh of Pacific Northwest Laboratories in 1981 on field experiences with HEPA filters, or the series of articles by Dr. Moeller in Nuclear Safety between 1975 and 1983 on problems in air cleaning systems, provide cause for concern. Unfortunately, similar instances in Europe have not been so well documented or publicized. Although not verifiable as having been moisture related, random and repeated unexplained failure of mini-pleat filters in normal service led KfK almost ten years ago to discontinue purchases of filters of this design altogether.

Previous full-scale tests at KfK with high humidity airflows have confirmed the potentiality of the failures to be found in the literature for filters in actual service. At design flows, instances of failure have been observed at pressure drops as low as 400 Pa. Even when the need for adequate safety margins is not regarded, this is well below the 1000 Pa that filters should be able to sustain for dust loading purposes alone. Filter units of the mini-pleat design, aged deep-pleat filters, and those with previous exposure to high air humidity appeared to be the most susceptible to the lower failure pressures. Failures for dust-loaded deep-pleat units have been recorded for air humidities as low as 50% RH. This is below the lower limit of demister effectiveness, i.e., 100% RH. With regard to European enthusiasm for the American concept of demisters with downstream heaters located upstream of HEPA and iodine filters, we can only speak for the situation in Germany. The containment buildings of all German pressurized water reactors completed within the past ten years or so are equipped with emergency recirculating air cleaning systems essentially equivalent to the Standby Gas Treatment Systems of the U.S. NRC Regulatory Guide 1.52.

As this leaves some relevant questions yet unanswered, why, despite the development of water repellant filer media and the concept of demisters with downstream air heaters, do reports of filter failures attributed to moisture continue to appear in the literature? Given that most of these occurred during otherwise "normal" operations, one could also ask what these incidents portend for a LOCA that results in the sudden release of large volumes of steam within a containment building.